Beam-foil lifetime measurements in Fe V and Fe VI

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The authors have recorded beam-foil spectra of Fe V and Fe VI between 1100 and 1900 Å at ion energies ranging from 0.4 to 1.5 MeV. For the first time, lifetimes have been measured for thirteen $3d\,^3 4p$ levels in Fe V and six $3d\,^2 4p$ levels in Fe VI. These lifetime results are not in agreement with the available theoretical values deduced from the transition probabilities calculated by Abbott.

I. INTRODUCTION

Very few beam-foil studies exist for low stages of ionization of iron (Fe I to Fe III).[1-6] None exist for intermediate stages of ionization. Whaling *et al.*[1] tried to identify Fe IV to Fe VI lines in their beam-foil spectra but they did not succeed because of the poor knowledge of these spectra at that time.

The lines of iron ions are well represented in stellar spectra because of the high abundance of iron. Until recently the analysis of hot-star spectra in the ultraviolet range suffered from the insufficient knowledge of spectra and from the lack of transition probabilities for the intermediate stages of ionization. Progress has now been made in the analysis of iron spectra,[7-9] but not in the determination of oscillator strengths or lifetimes.

For this reason we have recorded beam-foil spectra of iron in the vacuum-ultraviolet range and measured the first lifetime values for some $3d^3 4p$ and $3d^2 4p$ levels in Fe V and Fe VI, respectively. Our lifetime results are compared with theoretical values obtained from transition probabilities calculated by Abbott.[10]

II. EXPERIMENT

The experimental arrangement has been described in detail elsewhere.[11] The rf ion source of our 2-MV Van de Graaff accelerator was equipped with a modified exit channel constructed entirely of electrolytic iron; a mixture of 50% argon and 50% oxygen was employed as the buffer gas.[12,13] Iron beams of about 1 μA (8 mm in diameter) were obtained. The beam light was observed with a Seya-Namioka-type spectrometer equipped with an EMR-542G-08-18 photomultiplier tube. The length of the ion beam viewed by the spectrometer was about 0.2 mm. Intensity decays of transitions were measured by photon counting. The foil displacements were determined with an accuracy of 0.01 mm.

III. RESULTS AND DISCUSSION

A. Spectra

Spectra have been recorded between 1100 and 1900 Å at different energies ($0.4 \leq E \leq 1.5$ MeV; see Fig. 1). The full width at half-maximum of the lines is about 0.8 Å. At low energies, the spectra consist of numerous weak lines and very strong C I and C II lines. The latter originate from carbon ions ejected from the foil and are much stronger and more numerous with Fe^+ beams than with lighter-ion beams. Above 1 MeV strong Fe lines appear.

To determine the ionization stage of the emitting ion, we studied the variation of line intensity at the foil with the beam energy and compared the deduced relative beam-foil populations with the charge-state fractions measured by Smith and Whaling.[14] In Fig. 2 we show examples of such comparisons for the 1430.57- and 1272.07-Å lines in Fe V and Fe VI, respectively. Using this method one can determine the charge state i of the emitting ion with an error $\Delta i = \pm 1$. In the energy domain where the fractions of Fe III and Fe IV ions are maximum (see Fig. 2) we did not observe transitions in these ions. The strongest Fe III lines could be blended with carbon lines but we are somewhat puzzled not to see any Fe IV lines! These lines are probably embedded in the almost continuous background appearing in our low-energy spectra. In spectra recorded at higher energies ($E > 1$ MeV) we observed lines which could be attributed to ions with charge states 4, 5, or 6, studying their variations of intensity with the beam energy. Fe V and Fe VI lines have been classified

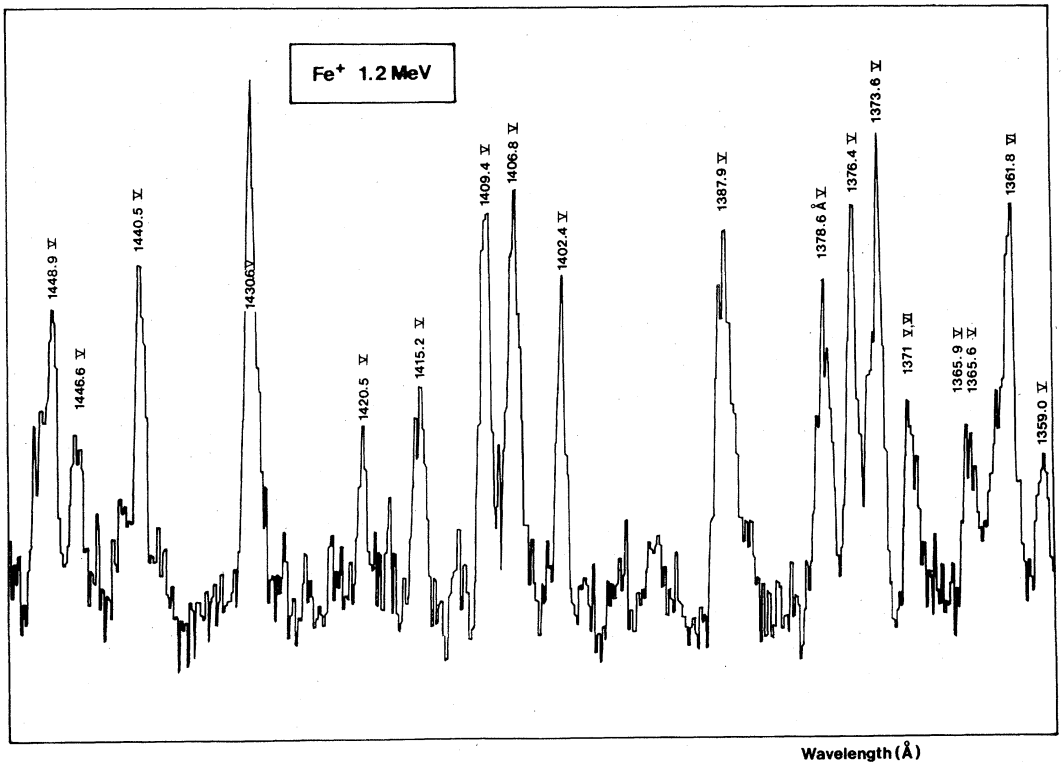

FIG. 1. Section of the beam-foil spectrum of iron obtained with 1.2-MeV Fe^+ ions.

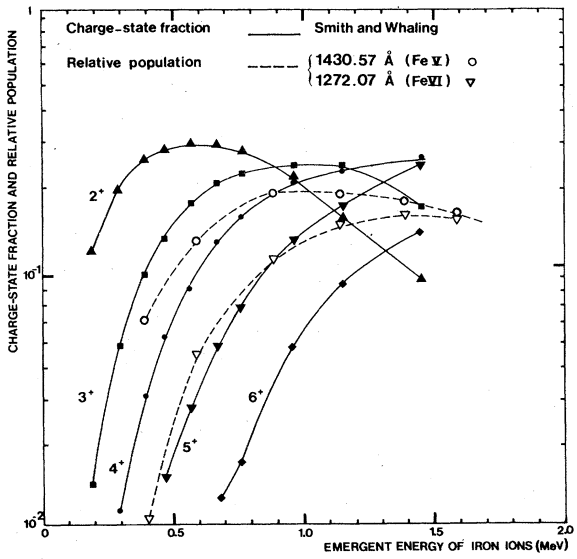

FIG. 2. Charge-state fractions in carbon foils for iron ions measured by Smith and Whaling (Ref. 14) and relative beam-foil populations at the foil for transitions in Fe V and Fe VI as a function of the emergent energy of iron ions. The two sets of curves are normalized at 0.9 MeV.

in the spectral range investigated by Ekberg,[7,9] but many Fe VII lines are still unclassified.

Numerous Fe V and Fe VI lines observed in our spectra are blended with lines in Fe V, Fe VI, and eventually Fe VII. Among about 150 lines observed in our spectra only 13 lines in Fe V and 6 lines in Fe VI were unblended or very weakly blended. All those lines for which the upper-level lifetimes have been measured correspond to strong lines in the sliding-spark spectra.[7,9] In particular, the 6 lines identified in Fe VI were the strongest lines appearing in the sliding-spark spectra; it is thus very unlikely that these lines can be blended with strong unclassified lines in Fe VII!

B. Lifetimes

The intensity decay curves were recorded using 1.25-MeV Fe^+ ions. They were analyzed by the curve-fitting program HOMER.[15] Our lifetime results for Fe V and Fe VI are given in Tables I and II, respectively. Each lifetime result is the mean value of at least four repeated measurements. The quoted errors represent plus or minus twice the standard deviation

TABLE I. Lifetime results in Fe v.

Wavelength (Å)	Transition [a]	Lifetime of upper level (nsec) This work	Theory [c]	Cascade lifetimes (nsec)	$R(0)$ [b]
1359.01	$(b\,^2D)\,^3D_3$-$(b\,^2D)\,^3F^0_4$	0.51 ± 0.04		~5	~0.1
1373.59	$(^4F)\,^5F_4$-$(^4F)\,^5F^0_4$	0.52 ± 0.04		~10	~0.05
1373.67	$(^4F)\,^5F_3$-$(^4F)\,^5F^0_3$				
1376.34	$(^4F)\,^5F_5$-$(^4F)\,^5F^0_5$	0.54 ± 0.02	0.28	~20	~0.07
1376.45	$(^4F)\,^5F_2$-$(^4F)\,^5F^0_2$		0.17		
1378.56	$(^4P)\,^5P_3$-$(^4P)\,^5D^0_4$	1.2 ± 0.2	0.66	~0.2	~1
1387.94	$(^2H)\,^3H_6$-$(^2H)\,^3I^0_7$	0.9 ± 0.2	0.57	~0.1	~3
1402.39	$(^2H)\,^3H_5$-$(^2H)\,^3I^0_6$	0.9 ± 0.1	0.57	~0.07, 12	~2
1415.20	$(^2H)\,^3H_4$-$(^2H)\,^3I^0_5$	0.9 ± 0.1	0.55	~20	~0.03
1406.82	$(a\,^2D)\,^3D_3$-$(a\,^2D)\,^3F^0_4$	0.40 ± 0.03	0.17	~5	~0.1
1409.03	$(^4F)\,^5F_3$-$(^4F)\,^5D^0_2$	0.30 ± 0.02	0.15	~2	~0.1
1409.22	$(^4F)\,^5F_4$-$(^4F)\,^5D^0_3$				
1409.45	$(^4F)\,^5F_5$-$(^4F)\,^5D^0_4$				
1430.57	$(^4F)\,^5F_5$-$(^4F)\,^5G^0_6$	1.4 ± 0.2	0.96	~0.4, 10	~2
1440.53	$(^4F)\,^5F_4$-$(^4F)\,^5G^0_5$	1.5 ± 0.3	0.97	~0.4, 10	~2
1448.85	$(^4F)\,^5F_3$-$(^4F)\,^5G^0_4$	1.5 ± 0.1	0.99	~0.1	~3
1456.16	$(^4F)\,^5F_2$-$(^4F)\,^5G^0_3$	1.7 ± 0.2		~0.3	~1

[a] Classification from Ekberg (Ref. 7); transitions $3d^4$-$3d^3 4p$.
[b] Replenishment ratio at the foil.
[c] Theoretical values determined from transition probabilities calculated by Abbott (Ref. 10).

σ of the mean (σ is estimated from the sample) combined with a 3% uncertainty in the ion velocity.

Some lines appearing in Tables I and II could in principle be blended.[7,9] We have been able to disentangle these blends through a careful analysis of our beam-foil spectra together with the sliding-spark results.[7,9]

1. Fe v

a. 1359.01 Å. We have neglected the blend with the less intense line at 1359.41 Å $[(^4F)\,^5F_1$-$(^4F)\,^3D^0_1]$.

b. 1373.6 Å. The intensity decay of this line has been measured on the low-wavelength side to avoid $(^4P)\,^3P_2$-$(^4P)\,^3D^0_3$ (1373.97-Å) and $(^2F)\,^3F_3$-$(^2F)\,^3G^0_4$ (1374.12-Å) lines. The $(a^2D)\,^3D_2$-$(a^2D)\,^3D^0_2$

TABLE II. Lifetime results in Fe vi.

Wavelength (Å)	Transition [a]	Lifetime of upper level (nsec) This work	Theory [c]	Cascade lifetimes (nsec)	$R(0)$ [b]
1228.60	$(^4G)\,^2G_{9/2}$-$(^4G)\,^2H^0_{11/2}$	0.33 ± 0.05	0.18	~2	~0.1
1253.68	$(^4G)\,^2G_{7/2}$-$(^4G)\,^2H^0_{9/2}$	0.33 ± 0.03	0.18	~2	~0.1
1272.07	$(^3F)\,^4F_{9/2}$-$(^3F)\,^4G^0_{11/2}$	0.81 ± 0.06	0.45	~0.1, ~5	~3
1285.37	$(^3F)\,^4F_{7/2}$-$(^3F)\,^4G^0_{9/2}$	0.62 ± 0.05	0.39	~0.1, ~5	~2
1296.87	$(^3F)\,^4F_{5/2}$-$(^3F)\,^4G^0_{7/2}$	0.59 ± 0.05	0.41	~0.1, ~5	~2
1361.82	$(^3F)\,^2F_{5/2}$-$(^3F)\,^2F^0_{5/2}$	0.42 ± 0.04	0.14	~3	~0.05

[a] Classification from Ekberg (Ref. 9); transitions $3d^3$-$3d^2 4p$.
[b] Replenishment ratio at the foil.
[c] Theoretical values determined from transition probabilities calculated by Abbott (Ref. 10).

(1373.67-Å) transition cannot contribute significantly to the observed line because the other components of the same multiplet are not observed in our spectra.

c. 1378.56 Å. To eliminate the influence of the line at 1378.1 Å [$(b^2D)^3D_1$-$(b^2D)^3F^0_2$], the measurement has been made on the long-wavelength side of the line.

d. 1387.94 Å. This line is slightly blended with the less intense transition $(^4P)^5P_1$-$(^4P)^3P^0_1$ (1388.20 Å). As we do not observe the other components of this intercombination multiplet, the measured lifetime was attributed to the $(^2H)^3I^0_7$ level.

e. 1402.39 Å *and 1406.82* Å. These lines are blended with the $(^4F)^3F_{3(4)}$-$(^4F)^3F^0_{3(4)}$ transitions at 1402.39 and 1406.67 Å. The most intense line of this ^3F-$^3F^0$ multiplet at 1400.24 Å is not observed in our spectra and the blends are negligible.

f. 1415.20 Å. This line could be blended with the $(^4F)^3F_3$-$(^4F)^3F^0_2$ and $(^2G)^3G_3$-$(^2G)^3G^0_4$ transitions at 1414.83 and 1415.15 Å, respectively. The first possibility of blend is rejected (see 1402.39- and 1406.82-Å lines). The second possible blend must be negligible because the other components of the $(^2G)^3G$-$(^2G)^3G^0$ multiplet are very weak in our spectra. Note that all (short-lived and long-lived) cascades are weak for the three observed lines of the ^3H-$^3I^0$ multiplet.

g. 1430.57 Å. We neglected the $(^2F)^1F_3$-$(^2F)^1D^0_2$ (1430.31-Å) and $(a^2D)^3D_3$-$(^4P)^3D^0_3$ (1430.75-Å) lines, which are weaker by more than a factor of 5.[7]

h. 1440.53 Å. This line could be blended with the $(^4P)^5P_1$-$(^4P)^5P^0_2$ line at 1440.79 Å and with the $(^4P)^5P_3$-$(^4P)^5P^0_3$ line at 1441.05 Å. These contributions can be neglected, the other components of this multiplet being absent from our spectra.

i. 1448.85 Å. There is a possible blend with the $(^2G)^1G_4$-$(^2G)^1F^0_3$ line at 1448.49 Å but the intensity of this line represents only one third of the 1448.85 Å line intensity.[7]

j. 1456.16 Å. We neglected the line at 1456.29 Å [$(^4P)^5P_2$-$(^4P)^5P^0_1$)] because its intensity is weaker by a factor of 5,[7] and moreover we do not observe other components of the same multiplet. Note that cascades are weak for the four observed lines of the ^5F-$^5G^0$ multiplet.

2. Fe VI

a. 1228.60 A. The $(^1D)^2D_{3/2}$-$(^1D)^2D^0_{5/2}$ (1228.73-Å) and $(^3F)^4F_{3/2}$-$(^3F)^4D^0_{3/2}$ (1228.96-Å) transitions cannot contribute significantly to the observed line because the other components of these multiplets are not observed in our spectra.

b. 1253.68 Å. Could be blended with the less intense $(^1D)^2D_{5/2}$-$(^3P)^4D^0_{3/2}$ line at 1253.05 Å, but the other components of this multiplet are not observed.

c. 1296.87 Å. The possible blend with the $(^1D)^2D_{3/2}$-$(^1D)^2F^0_{5/2}$ (1296.74-Å) line has been neglected because we did not observe the other components of that multiplet.

d. 1361.82 Å. This line could be blended with some Fe V lines. Other components of the same Fe V multiplets are not seen in our spectra, contrary to those of the $(^3F)^2F$-$(^3F)^2F^0$ multiplet in Fe VI. Thus we attribute the observed 1361.82-Å line entirely to Fe VI.

We have compared our lifetime results to the available theoretical values. Abbott[10] has performed *ab initio* calculations of the structure of Fe III–VI and calculated transition probabilities for all lines in the transition arrays $3d^n$ and $3d^{n-1}4s$–$3d^{n-1}4p$ using a Thomas-Fermi potential and including the relativistic corrections in the Breit-Pauli approximation. From his oscillator strengths we have calculated the theoretical lifetimes given in Tables I and II.

The theoretical lifetimes are systematically shorter than our results by factors of the order of 1.5–2.0. The cascade repopulations for all these levels are weak and cannot bias strongly the decay-curve analysis.

Abbott[10] has recently shown that, for iron-group ions there is a correlation between the ratios of the experimental lifetimes to his theoretical values and the average percent mixing of $3d^n$ and $3d^{n-1}4p$ due to configuration interaction.

The above-mentioned considerations clearly indicate the difficulty of obtaining experimental as well as theoretical lifetimes for heavy ions and emphasize the need for further investigations.

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